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Research article

Global warming and shifts in cropping systems together reduce China's rice production

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ABSTRACT

Climate warming is widely expected to affect rice yields, but results are equivocal and variation in rice cropping systems and climatic conditions complicates country-scale yield assessments. Here we show, through meta–analysis of field warming experiments, that yield responses to warming differ strongly between China's rice cropping systems. Whereas warming increases yields in "single rice" systems, it decreases yields in "middle rice" systems and has contrasting effects for early and late rice in "double rice" systems. We further show that the contribution of these cropping systems to China's total rice production has shifted dramatically over recent decades. We estimate that if the present structure of rice cropping systems persists, warming will reduce China's total rice production by 5.0% in 2060. However, if the recent decline in the area of double rice systems continues, China's rice production may decrease by 13.5%. Our results underline the need for maintaining the current area of China's "double rice" cropping system and for technological innovations in multiple rice cropping systems to ensure food security in a warming climate.

1. Introduction

With more than half of all people depending on rice as a primary source of caloric intake, rice is the world's most important staple food (Maclean et al., 2002). Global demand for rice is expected to increase by 28% in the next three decades (Alexandratos and Bruinsma, 2012). As the world's largest rice producer, China will play a central role in meeting these demands. China also consumes and imports more rice than any other country (FAOSTAT, 2017), meaning that even small changes in China's rice production will strongly affect the global rice market.

The global mean air temperature is predicted to rise by 0.75–4.0 °C by 2100 (IPCC, 2013). Because temperature plays a key role in crop development and growth (Zhang et al., 2013; García et al., 2015), future climatic warming is widely expected to affect global rice production (Peng et al., 2004; Welch et al., 2010; Lobell et al., 2011; van Groenigen et al., 2013; Challinor et al., 2014; Zhao et al., 2017a, 2017b). However, air temperature and precipitation patterns vary strongly across China, suggesting that climatic warming impacts on Chinese rice yields will vary both in space and time (Tao et al., 2013; Chen et al., 2017).

Three rice cropping regions cover 96% of China's rice growing area (PINC archives, 2016), each with its own cropping system and rice type: single rice cropping systems in the Northeast ("single rice"), middle rice cropping systems in East and central China ("middle rice"), and double rice cropping systems in the South ("early rice" and "late rice") (Fig. 1). In the single rice cropping system, rice seedlings are transplanted in May and harvested by the end of September or the beginning of

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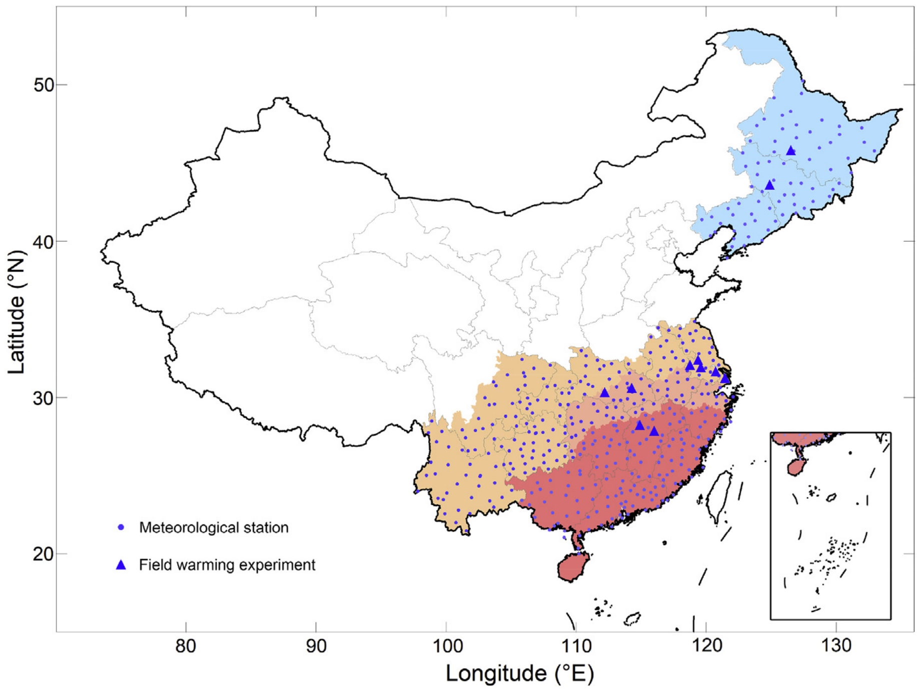

Fig. 1. Map of the major Chinese rice cropping regions and field warming experiments included in our analysis. The single rice cropping region is indicated in blue, the middle rice cropping region is indicated in light orange, and the double rice cropping region is indicated in light red. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

October. In the middle rice cropping system, the preceding dryland-crops (wheat, barley, rapeseed, vegetable, green manure, etc.) are harvested by the end of May or the land is left fallow until then; rice plants are transplanted or direct-seeded in June and harvested in October. In the double rice cropping system, the early rice is transplanted or direct-seeded by the end of April and harvested by the end of July; the late rice is transplanted by the end of July and harvested by the end of October or the beginning of November. After the harvest of late rice, some farmers grow dryland-crops (rapeseed, vegetables, green manure, etc.) or leave the land fallow during the winter and early spring.

The past decades have witnessed several important changes in the structure of China's rice cropping systems. Due to rapid urbanization, rice paddies made way for housing, industry and infrastructure. Furthermore, migration to urban areas decreased rural labor availability and raised labor costs. Both trends affected rice agriculture across China (Tong et al., 2003; Chen et al., 2013; Deng et al., 2019). During the 1980s in what is now the middle rice cropping region (East and Centre of China; Fig. 1), large areas of double rice cropping systems were converted to middle rice cropping, which require less labor (Chen et al., 2013; Yuan et al., 2019). A second shift occurred during the period of 1996–2005 in the current double rice cropping region (South of China), where large areas of paddy field were either converted into non-rice cropland or to middle rice cropping systems. In 2006, the Chinese government implemented a strict policy in paddy field protection for staple food self-sufficiency. With this new policy, rice farmers cannot convert their paddy fields into other land use, but they can adjust double rice cropping to middle rice cropping to decrease labor cost. However, urbanization rates are expected to remain high in the coming decades (World Bank, 2014), and domestic rice production cost and price are substantially higher than on the international market (Selim, 2015). Therefore, without strong policy incentives, the area of double rice cropping systems is predicted to decrease further, as it is being converted into middle rice systems.

All three Chinese rice growing regions have experienced warming from 1980 to 2015 during the rice growing season (Table 1). Even though the three regions have very different climates, previous efforts to synthesize rice yield responses to warming did not consider differences between rice cropping systems (van Groenigen et al., 2013; Challinor et al., 2014; Zhao et al., 2017a; Zhao et al., 2017b). Here, we present a comprehensive study to quantify the impact of future warming on Chinese rice production (Fig. 2). First, we conducted a meta-analysis of field warming experiments to assess the effect of rising temperatures on rice yield in Chinese rice cropping systems (Data set 1). Second, we analyzed how the contribution of these cropping systems to China's total rice production has changed in recent decades. Finally, we used these data to estimate future changes in total Chinese rice production, taking into account projected warming trajectories and changes in rice cropping area for each system.

2. Materials and methods

2.1. Meta-analysis

We collected peer-reviewed papers on warming and rice yields published before September 2018 from Web of Science and supplemented these with data collected from ongoing warming experiments (Data set 1). To be included in our dataset, the studies had to meet the following criteria: (i) The experiment was conducted in China, under field conditions with replicates; (ii) Temperatures were increased by ≤ 2 °C in the warmed treatments, because the global community agreed with the Paris agreement to limiting global warming to 2.0 °C (UNFCCC, 2015); (iii) Temperatures were increased during the entire rice growing season in the warmed treatments (i.e., studies on post-anthesis warming were excluded). In total, we collected 70 observations from 13 experiments (Fig. 1, Table 2). Detailed information on experimental conditions and agricultural practices for each study included in our meta-analysis can be found in Data set 1.

We quantified the impacts of warming on rice yield using the natural logarithm of the response ratio (R), a widely used effect size metric in meta-analysis (Hedges et al., 1999):

$$\mathrm{Ln}R = \mathrm{Ln}\ (xw/xc)$$

where the xw is the rice yield of warmed treatment and xc is the rice yield of the control treatment. Each value of LnR was weighted by the inverse of its variance; missing variances were estimated using the average coefficient of variation across our dataset. The response ratio was log-transformed to normalize the data and to ensure that variations in the yields in control treatments and warmed treatments have similar

Table 1
Average values and warming trends of daily mean, maximum and minimum temperatures during rice growing seasons in the major Chinese rice cropping system over 1980–2015.

Rice type	Temperature index	Daily mean temperature	Daily maximum temperature	Daily minimum temperature
Single rice	Average value (°C)	18.78 ± 0.54	24.42 ± 0.61	13.57 ± 0.54
	Warming trend (°C/decade)	0.31**	0.29**	0.36**
Middle rice	Average value (°C)	23.01 ± 0.43	27.96 ± 0.54	19.32 ± 0.41
	Warming trend (°C/decade)	0.34**	0.39**	0.32**
Early rice	Average value (°C)	23.26 ± 0.54	27.66 ± 0.64	19.99 ± 0.49
	Warming trend (°C/decade)	0.28**	0.29**	0.29**
Late rice	Average value (°C)	25.98 ± 0.48	30.66 ± 0.55	22.60 ± 0.45
	Warming trend (°C/decade)	0.25**	0.26**	0.25**

Results are presented as mean ± standard deviation. ** indicate significant warming trends at $p < 0.01$. Temperature data for single rice, middle rice and double rice systems were collected from 72, 219, and 225 meteorological stations of the Chinese meteorological administration (CMA), respectively (Fig. 1). See Table S1 for details.

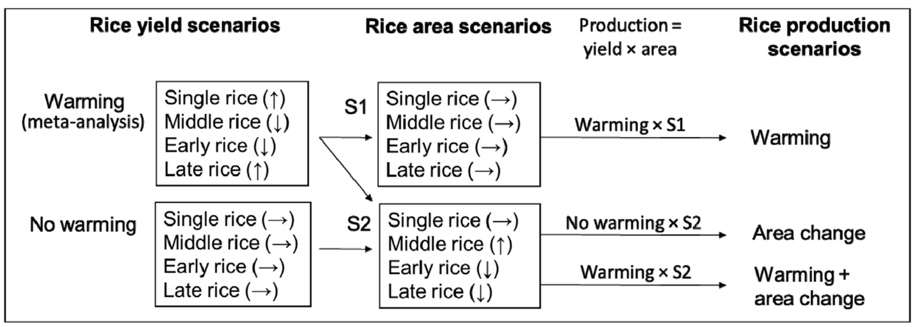

Fig. 2. The individual components of our approach to estimate future changes in Chinese rice production. S1, Scenario 1 (fixed cropping area); S2, Scenario 2 (changing cropping area).

impacts on overall average treatment effects (Hedges et al., 1999).

Several environmental and experimental factors have been suggested to affect rice yield responses to warming, including temperature increase, rice cultivar and warming regime (Peng et al., 2004; Challinor et al., 2014; Tao et al., 2013). To test whether any of these factors affected the response of rice yield to warming, we collected the following information for each experiment in the Data set 1: soil pH, soil organic carbon (g kg^{-1}), warming regime (daytime, nighttime, or all day), warming technique (passive warming, active warming, and passive + active warming), temperature increase (°C), rice cultivar (Japonica vs. Indica), atmospheric CO_2 (ambient vs. elevated), and rice types (single, middle, early, and late). We used the "glmulti" package in R to assess the relative importance of experimental factors in determining treatment effects, analyzing our data with all possible models that could be constructed using combinations of the factors described above (Terrer et al., 2016; Jiang et al., 2019).

We used the rma.mv function in the "metafor" package to perform a mixed-effects meta-analysis in R and a Wald-type test to determine whether treatment effects were statistically different between experimental classes (Viechtbauer, 2010). We included "experimental site" as a random effect because several experiments contributed more than one effect size to our data set. To ease interpretation, we back-transformed the results of LnR and reported treatment effects as the percentage change [$(R - 1) \times 100$].

2.2. Climatic warming

We used three General Circulation Models (that is, BCC-CSM1.1(m), BNU-ESM, and MIROC-ESM-CHEM) to project the ensemble mean future temperature of rice growing seasons in China. The three models

Table 2
Overview of warming experiments included in our meta-analysis; further details of each experiment can be found in Dataset 1.

Location	Cropping system	Duration (yr)	Warming technique[a]	Reference
Changshu	Middle rice	4	Active	Cai et al. (2016), Wang et al. (2016)
Danyang	Middle rice	4	Active or Passive	Chen et al. (2017)
Gongzhuling	Single rice	3	Passive	Chen et al. (2017)
Haerbin	Single rice	1	Active	Dong (pers. comm.)
Haerbin	Single rice	1	Active	Zhang (pers. comm.)
Jingzhou	Double rice	3	Active + Passive	Wang et al. (2018a)
Jinxian	Double rice	1	Active	Chen (pers. comm.)
Jinxian	Double rice	3	Active or Passive	Chen et al. (2017)
Nanjing	Middle rice	3	Active	Dong et al. (2011)
Shanggao	Double rice	1	Active	Huang (pers. comm.)
Shanghai	Middle rice	1	Active	Cheng et al. (2013)
Wuhan	Middle rice	1	Active	Yang et al. (2017)
Yangzhou	Middle rice	4	Active	Li et al. (2017), Wang et al. (2018b)

[a] Active warming involves warming by infrared heaters or heating pipes. Passive warming involves open top chambers or reflective curtains. "Active + Passive" refers to studies in which both techniques were applied at the same time within the same experiment. "Active or Passive" refers to studies that included both experiments that used active warming, and other experiments that used passive warming.

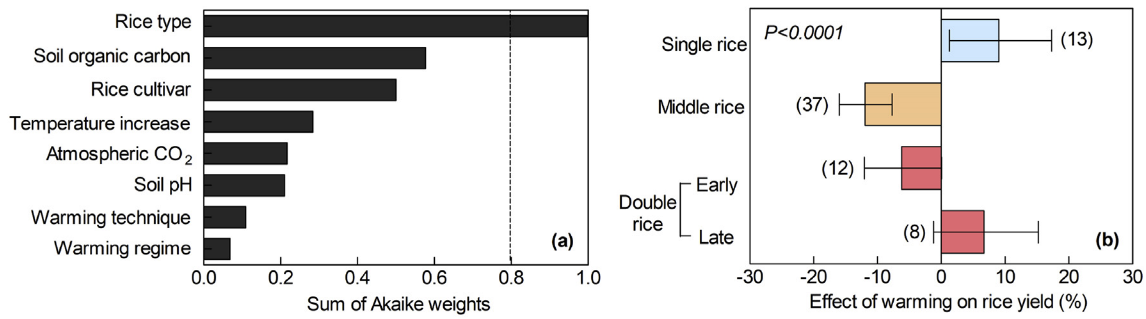

Fig. 3. Results from a meta-analysis on the effect of warming on rice yield. a, Model-averaged importance of the predictors of warming effect on rice yield. The importance is based on the sum of Akaike weights derived from model selection using AICc (Akaike's Information Criteria corrected for small samples). Cut-off is set at 0.8 (dashed line) to differentiate important from non-essential predictors. b, the effects of warming on rice yield. Numbers between brackets indicate the number of observations. Error bars indicate 95% confidence intervals.

participate in the Coupled Model Intercomparison Project phase 5 (CMIP5) Representative Concentration Pathway 4.5 (RCP4.5) (Taylor et al., 2012) and are widely applied in climate impact studies in China (Miao et al., 2014; Chen and Frauenfeld, 2014; Yang et al., 2016). For each rice type, we calculated the mean value and spatial variation using data from all model grid cells in the corresponding rice growing region (Fig. 1).

2.3. Cropping system structure changes

Data on total sown rice area and rice yield for each rice type from 1980 to 2015 were collected from the Planting Information Network of China (PINC archives, 2016).

We considered two scenarios of changes in the area of Chinese rice cropping systems.

2.3.1. Scenario 1 (fixed cropping area)

In the first scenario, the total area of each rice cropping system remains unchanged between 2015 and 2060. This scenario assumes that the Chinese government will implement strict policy in paddy field protection and provide strong support for double rice cropping, as outlined in the National Plan for Crop Planting Structure Adjustment (2016–2020).

2.3.2. Scenario 2 (changing cropping area)

In the second scenario, the changes in cropping system area for double and middle rice between 1980 and 2015 will continue between 2015 and 2060. To estimate future changes in these areas, we fitted an exponential function to the changes in double rice cropping area between 1980 and 2015 (Fig. S1), and then used this equation to estimate the double rice area between 2015 and 2060. Because recent government regulations stipulate that rice farmers cannot convert their paddies to other forms of land use, we assumed that the decreased double rice area will be converted to middle rice. In the single rice cropping region, land availability and water resources are limiting further expansion of the rice planting area (Liu et al., 2005). Thus, the single rice area remained unchanged in both scenarios.

2.4. Warming impact on rice production

Based on the effects of warming on rice yield and rice planting areas of different rice cropping systems, we estimated the effects of warming on China's total rice production (*EP*, %) under the two cropping system scenarios described above:

$$Y_i = (1 + \alpha_i) \times Y_{2015i}$$

$$EP = (\Sigma Y_i \times A_i / TP_{2015} \text{-} 1) \times 100$$

where Y_i is the projected per hectare rice yield for rice type *i*; αi is the impact of warming on rice yield for rice type *i*, based on the results of our meta-analysis (i.e. *R*-1); *Ai* is the projected sown area of rice type *i*; Y_{2015i} is the average per hectare rice yield of rice type *i* in 2015 (Fig. S2); TP_{2015} is the total rice production in 2015. Finally, we also quantified the effects of changes in rice planting area of different rice cropping systems (that is, $\alpha_i = 0$) on China's rice production in the absence of warming ("area change"). Because yield responses to warming are non-linear (van Groenigen et al., 2013), we did not extrapolate our results beyond the average temperature increase applied in the experiments in our meta-analysis.

3. Results

3.1. Warming and rice yield

Our meta-analysis clearly shows that the effects of warming on rice yield differs between rice types. Rice type accounted for more of the variation in warming responses of rice yield than a wide range of other experimental and environmental factors (Fig. 3a). Model selection analysis showed that all top-supported models included rice type as a moderator. Furthermore, the model that only contained rice type was the most parsimonious model within 2 AIC units (Table S2). Experimental warming increased yields of single rice by 9.0% and yields of late rice by 6.7%, but it reduced yields of middle rice by 11.9% and yields of early rice by 6.2% (Fig. 3b). Averaged across our dataset, experimental warming increased mean air temperature by ~1.4 °C for all rice types (Fig. S3).

3.2. Climatic warming projections

The three General Circulation Models project that the air temperature during the rice growing season will continue to increase in all Chinese rice cropping regions (Fig. S4). The average temperature increase in the warming experiments that were included in our analysis, i.e. 1.4 °C, approximately matched the projected warming rates between 2015 and 2060 for all three rice cropping regions.

3.3. Cropping system structure changes

From 1980 to 2015, the area of double rice cropping system shrunk by nearly 50%, while the area of middle rice cropping system increased by a third, and the area of single rice cropping system nearly tripled (Fig. 4a). The decrease in cropping area of early rice (EA) and late rice (LA) between 1980 and 2015 could be described by $EA_i = 11.214e^{-0.0216x}$ ($r^2 = 0.93$, $p < 0.01$) and $LA_i = 11.537e^{-0.0198x}$ ($r^2 = 0.91$, $p < 0.01$), respectively (Fig. S1). Based on these equations, the area of middle rice cropping system will increase by 26% from 2015 to 2060; the area of double rice cropping system will decrease by 60%, and the total rice cropping area will be

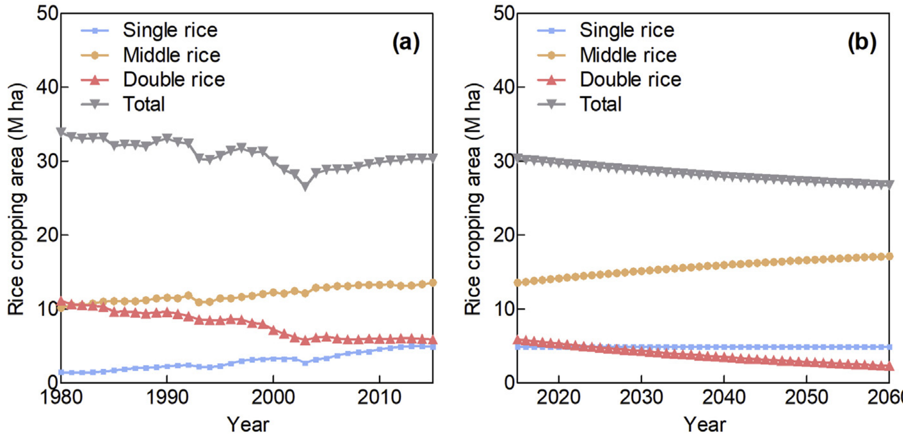

Fig. 4. Changes in the area of each rice cropping system. Change in the area of each rice cropping system over 1980–2015 (a); predicted area of each cropping system and total rice cropping area (b). Because the double rice area is harvested twice per year, it was counted twice to calculate the total rice cropping area.

reduced by 12% (Fig. 4b).

3.4. Warming impact on rice production

The average temperature increase applied in studies in Data set 1 matches expected temperatures in 2060 for all three rice cropping regions. Thus, we assumed that the results of our meta-analysis were indicative of warming effects on rice yield in 2060. Under the "warming" scenario (i.e. warming without changes in area), China's total rice production in 2060 would be reduced by 5.0%. However, under the "warming + area change" scenario, warming and the decrease in double rice cropping system reduce China's total rice production by 13.5% in 2060 compared to 2015 (Fig. 5). Changes in the area of rice cropping systems without warming would reduce China's total rice production by 7.4%.

4. Discussion

Our meta-analysis of field warming experiments shows that the effects of warming on rice yield differed between single rice, middle rice and double rice. These results are consistent with analyses of long-term

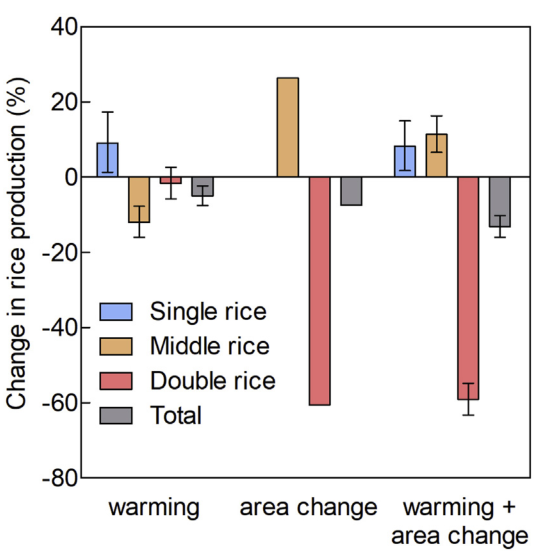

Fig. 5. Changes in rice production (i.e. total amount of rice produced in China) between 2015 and 2060 under the three scenarios outlined in Fig. 2. Results are shown for each rice cropping system separately, and for total rice production. Error bars indicate 95% confidence intervals.

data sets of climatic variables and rice yields (Tao et al., 2008, 2013; Wang et al., 2014; Xiong et al., 2014). For instance, Tao et al. (2008) and Xiong et al. (2014) found that warming in recent decades increased rice yields in northeast China (single rice in our study). Similarly, Tao et al. (2013) showed that yields of single rice in North Eastern China Plain (single rice in our study) and late rice were significantly and positively correlated with mean temperature of the rice growing season during 1981–2009. In contrast, yields of the single rice in the middle and lower reaches of Yangtze River (middle rice in our study) were significantly and negatively correlated with mean temperature.

Why do yield responses to warming differ between cropping systems? Rice growth and development are highly sensitive to temperature, especially during the reproductive period (Satake and Yoshida, 1978; Estrella et al., 2007; Tao et al., 2013; Espe et al., 2017). For rice yield formation, the optimal temperature is approximately 25–30 °C; higher temperatures reduce rice yield through inducing spikelet sterility, whereas lower temperatures slow down pollen development and grain filling (Matsui et al., 1997; Kim et al., 2011; Giorno et al., 2013). Under current climatic conditions, air temperatures during the reproductive periods of early and middle rice are similar to or exceed optimal temperatures, while temperatures are substantially lower than the optimal in late and single rice seasons (Table S1). Thus, whereas climate warming will make temperatures less favorable for early and middle rice, temperatures will become more favorable for late and single rice.

Our estimates of future warming impacts on rice yields and rice production might be underestimates for two reasons. First, our approach did not account for future changes in the spatial distribution of rice cropping systems; we used warming effects of middle rice yield in the current middle rice cropping region to estimate warming impacts on the yield of future middle rice, even though some of the future middle rice will be grown in the current double rice cropping region. Average daily temperatures in the current double rice cropping region are higher than in the current middle rice cropping region (Table S1), suggesting stronger negative warming effects on future middle rice (van Groenigen et al., 2013). Second, our analysis considered only the direct effects of warming on yield, but indirect effects of warming can amplify stress, further suppressing rice yield, for example through increased pests and disease (Piao et al., 2010; Barford, 2013). Extreme temperatures and droughts are also more likely to occur with rising temperatures, and both will negatively affect crop yields even further (Meehl and Tebaldi, 2004; Sherwood and Fu, 2014).

Our results suggest that the combined impact of global warming and shifts in rice cropping systems may severely reduce China's rice production. Indeed, the 13.5% decrease in China's rice production in the "warming + area change" scenario exceeds the amount of rice available on the current global market (FAOSTAT, 2017). On the other hand, yield projections of the “warming” scenario suggest that through smart agricultural policy, such dramatic consequences may be partly avoided. Our results highlight the importance of double rice cropping systems to bolster food security in a warmer climate, as these systems are less susceptible to warming-induced yield losses than middle rice and produce two yields per year. Thus, to prevent large-scale reductions in rice production, double rice cropping systems should be promoted.

We propose that future research efforts should focus on technological innovations for multiple rice cropping systems. To increase the chance of these innovations being adopted, these should reduce labor costs, or boost rice yields with minimal extra labor (Yuan et al., 2019). For instance, new and simplified mechanical rice planting techniques may help to reduce production input and save labor force demand (Farooq et al., 2011), making double rice cropping systems more attractive to farmers.

Several other agronomic strategies may also help to mitigate negative effects of warming on rice production. First, rice sowing dates may be optimized to mitigate high temperature stress during the reproductive period. For instance, delays in the planting date in middle rice systems can induce shifts towards lower temperatures in the grain filling stage, thereby promoting rice yields (Hu et al., 2017). Second, rice varieties with longer growth periods may offset the negative effect of warming on rice yield (Liu et al., 2012; Tao et al., 2013). Indeed, from 1981 to 2009, the adoption of cultivars with longer growth periods contributed to higher yields in single rice and middle rice systems (Tao et al., 2013). Third, ratoon rice planting (i.e., growing a second rice crop from the stubble left behind after the main-crop harvest) may also boost rice production (Harrell et al., 2009; Yuan et al., 2019); farmers can plant once using direct-seeding and harvest twice, which can greatly reduce labor cost and increase farmers' income. When double rice systems are being replaced by middle rice systems, ratoon rice can be a viable option to achieve both high annual yields and to increase profits while reducing environmental impacts (Yuan et al., 2019). Although the ratoon rice area is increasing (Yuan et al., 2019), precise data are still unavailable. Thus, ratoon rice was not considered in our scenarios. We suggest that to improve yield predictions, future assessment should aim to quantify the contribution of ratoon rice to overall Chinese rice production. Finally, new rice cultivar breeding programs may help to enhance rice quality and improve resistance to abiotic and biotic stresses (Zhang, 2007; Yamano et al., 2016; Atlin et al., 2017), including high temperature stress during the reproductive period (Reynolds et al., 2016; Hu et al., 2017). Current Chinese farm yields for single rice and double rice are 72% and 66% of the potential yields, respectively (Deng et al., 2019). Closing exploitable yield gaps in current rice areas would increase Chinese rice production by 15%, which may offset warming-induced reductions in yield (Deng et al., 2019). As the world's largest rice producer, China faces the difficult challenge of securing the global rice supply while our climate continues to change.

Declaration of competing interest

We declare no conflict of interests.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gfs.2020.100359.

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